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Modeling of the Continuous Absorption of Electromagnetic Radiation in Dense Hydrogen Plasma

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Abstract. In this work is examined a new modeling way of describing the continuous absorption of electromagnetic (EM) radiation in a dense partially ionized hydrogen plasmas with electron densities about $5 \cdot 10^{18}$ cm^{-3} - $1.5 \cdot 10^{19}$cm^{-3} and temperatures about $1.6 \cdot 10^4$ K - $2.5 \cdot 10^4$ K in the wavelength region 300nm $< \lambda <$ 500nm. The obtained results can be applied to the plasmas of the partially ionized layers of different stellar atmospheres.

Key words: ISM: extinction – stars: continuous absorption

1. INTRODUCTION

In this paper testing is started of a new model way of describing some of atomic photo-ionization processes in dense strongly ionized plasmas, which is based on the approximation of cut-off Coulomb potential. By now this approximation has been used only in order to describe transport properties of dense plasmas (see for example Mihajlov et al. (1989)), but it was clear that it could be applied to the mentioned absorption processes in non-ideal plasmas too. Because of exceptional simplicity of the hydrogen atom, for the first application of the mentioned approximation the following photo-ionization processes are chosen here:

$$\varepsilon_\lambda + H^*(n,l) \rightarrow H^+ + e_E, \qquad (1)$$

where ϵ_λ is the energy of the photon with wavelength λ, n and l - principal and orbital quantum numbers of hydrogen atom excited states, e_E - the free electron in one of the states with energy $E = \hbar^2 k^2/2m$, and m and $\hbar$ - the electron mass and Plank's constant. It is clear that describing the processes of the type of Eq. (1) in strongly non-ideal plasmas is one of the most complicated problems. Namely, while in weakly and moderately non-ideal plasma the interaction of an excited atom with its neighborhood can be neglected, as for example in Solar photosphere (Mihalas (1978); Mihajlov et al. (2007)), or described within the framework of a

perturbation theory, this is not possible in strongly non-ideal plasmas. This is due to the fact that in such plasmas the energy of the mentioned interaction reaches the order of the corresponding ionization potential.

Here a new model method having a semi-empirical character of determination of the spectral absorbtion coefficients, characterizing the bound-free (photo-ionization) processes (1) in strongly non-ideal hydrogen plasmas, is presented. As landmarks we take hydrogen plasmas with electron densities $N_e \sim 1 \cdot 10^{19}\mathrm{cm}^{-3}$ and temperatures $T \approx 2 \cdot 10^4\mathrm{K}$, which were experimentally studied in Vitel et al. (2004). The presented method is tested within the optical range of photon wavelengths $350\mathrm{nm} \le \lambda_{h\nu} \le 500\mathrm{nm}$.

2. THEORY

The absorption processes (1) in non-ideal plasma are considered here as a result of radiative transition in the whole system "electron-ion pair (atom) + the neighborhood", namely: $\epsilon_\lambda + (H^+ + e)_{n,l} + S_{rest} \rightarrow (H^+ + e)_E + S'_{rest}$, where S_{rest} and S'_{rest} denote the rest of the considered plasma. However, as it is well known, many-body processes can sometimes be simplified by their transformation to the corresponding single-particle processes in an adequately chosen model potential. Here, in accordance with the previous paper (Mihajlov et al. 1989) the screening cut-off Coulomb potential is taken as an adequate model potential, which can be presented in the form

$$U_c(r) = \begin{cases} -e^2/r + e^2/r_c, & 0 < r \le r_c, \\ 0, & r_c < r < \infty, \end{cases} \tag{2}$$

which is illustrated by Fig. 1. Here e is the modulus of the electron charge, r - distance from the ion, and cut-off radius r_c - the characteristic screening length of the considered problem. Namely, within this model it is assumed that quantity $U_{p;c} = -e^2/r_c$ is the mean potential energy of an electron in the considered hydrogen plasma. It is important that the cut-off radius r_c can be determined as a given function of N_e and T, using two characteristic lengths: $r_i = [k_B T/(4\pi N_i e^2)]^{1/2}$ and $r_{s;i} = [3/(4\pi N_i)]^{1/3}$, where N_i and $r_{s;i}$ are the H^+ density and the corresponding Wigner-Seitz's radius and k_B - Boltzman's constant. Namely, taking that $N_i = N_e$ and

$$r_c = a_{c;i} \cdot r_i, \tag{3}$$

we can directly determine the factor $a_{c;i}$ as a function of ratio $r_{s;i}/r_i$, on the basis of the data about the mean potential energy of the electron in the single ionized plasma from Mihajlov et al. (2009). The behavior of $a_{c;i}$ in a wide region of values of $r_{s;i}/r_i$ is presented in Fig.2.

In diluted hydrogen plasma (see for example Mihalas 1978) the spectral absorption coefficients, characterizing the photo-ionization processes (1) can be described within the approximation of the non-perturbed energy levels in the potential $U_c(r)$, namely: $\kappa_{ph}^{(0)}(\lambda; N_e, T) = \sum_{n,l} N_{n,l} \cdot \sigma_{ph}(\lambda; n, l, E_{n,l})$, where $N_{n,l}$ is the density of the atoms in the realized excited states with given n and l, and $\sigma_{ph}(\lambda; n, l, E_{n,l})$ - the corresponding photo-ionization cross section for $n \ge 2$. According to the above mentioned, it cannot model the absorption coefficients of the dense non-ideal plasmas described in Vitel et al. (2004).

It can be shown, using the results from Adamyan (2009), that $\kappa_{ph}(\lambda; N_e, T)$ can be obtained within the approximation based on adequately chosen shifts $\Delta_{n,l}$ and broadenings $\delta_{n,l}$ of the energy levels with given n and l. It is assumed that energies ϵ of the perturbed atomic states are dominantly grouped around energy $\epsilon_{n,l}^{(max)} = E(n,l) + \Delta_{n,l}$, inside the interval $(\epsilon_{n,l}^{(max)} - \delta_{n,l}/2, \epsilon_{n,l}^{(max)} + \delta_{n,l}/2)$, similarly to the known cases (Gaus, Lorentz, uniform etc.).

Let us note that it is possible to describe the quantity Δ_n as a function of N_e. Namely, for well-known physical reasons all shifts $\Delta_{n,l}$, and consequently Δ_n, have to change proportionally with the density of the perturbers, the relative atom-perturber velocity and the characteristic perturbation energy. Consequently, we will have that: $\Delta_n \sim N_e \cdot v_{ea}(T) \cdot e^2/l(N_e, T)$, where $v_{ea}(T)$ and $l(N_e, T)$ are the characteristic electron-atom velocity and distance. On the basis of the results of Mihajlov et al. (2009) in the considered cases ($N_e \sim 1 \cdot 10^{19}\text{cm}^{-3}$, $T \sim 2 \cdot 10^4\text{K}$) any relevant characteristic length has to be close to the radius r_i. From here, since $v_{ea}(T) \sim (k_B T)^{1/2}$ and $r_i \sim (k_B T/N_e)^{1/2}$, the relation follows

$$\Delta_n \approx Const. \cdot N_e^{3/2}, \tag{4}$$

which is in accordance with Adamyan (2009) and can be useful in further considerations.

Here, we will describe the perturbed atomic states in the first order of the perturbation theory and, in accordance with what was said above, we will have it that

$$\kappa_{ph}(\lambda; N_e, T) = \sum_{n,l} N_{n,l} \cdot \frac{1}{\delta_n} \int\limits_{\epsilon_{n,l}^{(max)} - \delta_n/2}^{\epsilon_{n,l}^{max} + \delta_n/2} \frac{\varepsilon_\lambda}{\varepsilon_\lambda + \epsilon} \cdot \sigma_{ph}(\lambda^{(\epsilon)}; n, l, E_{n,l}) d\epsilon, \tag{5}$$

where $n \geq 2$, $\epsilon_{n,l}^{(max)} = E_{n,l} + \Delta_n$, and $\sigma_{ph}(\lambda^{(\epsilon)}; n, l, E_{n,l})$ is the corresponding photo-ionization cross section for $\lambda^{(\epsilon)} = \lambda \cdot \varepsilon_\lambda / (\varepsilon_\lambda + \epsilon)$, i.e. for the wavelength of the photon with energy $(\varepsilon_\lambda + \epsilon)$.

3. RESULTS AND DISCUSSION

In this paper the approximation of cut-off Coulomb potential (2) is applied to the modeling of spectral absorption coefficients of the hydrogen plasma, obtained in Vitel et al. (2004) in two experiments: a short and a long pulse, respectively. In the first case (short pulse) plasma with $N_e = 1.5 \cdot 10^{19}\text{cm}^{-3}$ and $T = 2.3 \cdot 10^4\text{K}$ was studied, while in the second case (long pulse) - one with $N_e = 6.5 \cdot 10^{18}\text{cm}^{-3}$ and $T = 1.8 \cdot 10^4\text{K}$. It has been found that: $r_c = 44.964$ a.u. for a short pulse, and $r_c = 55.052$ a.u. for the long one.

In order to compare the obtained theoretical results with the experimental data from Vitel et al. (2004), we had to take into account other relevant absorption processes, namely: $(e + H^+)$-inverse "bremsstrahlung", as well as H^- and H_2^+ absorption continuums, which cannot be neglected in the considered hydrogen plasmas. Therefore, when comparing our theoretical results with the experimental data from Vitel et al. (2004) we use the total spectral absorption coefficient $\kappa_{tot}(\lambda)$ given by: $\kappa_{tot}(\lambda) = \kappa_{ph}(\lambda) + \kappa_{add}(\lambda)$, where the member $\kappa_{ph}(\lambda) \equiv \kappa_{ph}(\lambda; N_e, T)$ is

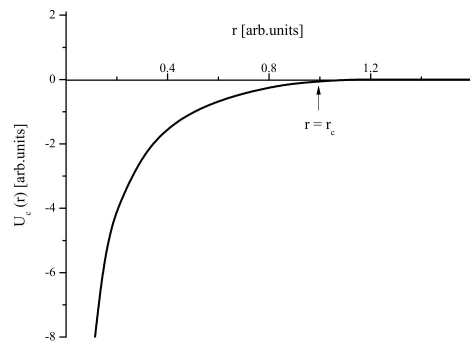

Figure 1: Cut-off potential $U_c(r)$, where r_c is cut-off parameter.

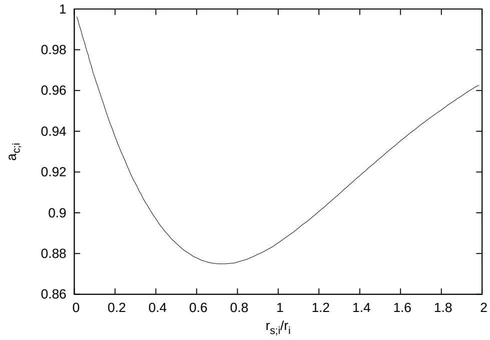

Figure 2: The parameter $a_{c;i} \equiv r_c/r_i$ as the function of the ratio $r_{s;i}/r_i$.

given by Eq. (5), while the member $\kappa_{add}(\lambda)$ is the sum of the absorption coefficients of all additional processes. Let us note that electron-ion process is described by the absorption coefficient from Sobel'man (1979), while the electron-atom and ion-atom processes - by the ones determined as in previous paper (Mihajlov et al. 2007) dedicated to the same absorption processes in the solar photosphere.

In accordance with the aims of this work the calculations of the total absorbtion coefficient, are performed for both cases (short and long pulse) in wide regions of values of shifts (Δ_n) and broadening (δ_n) of atomic levels with $n \geq 2$. The calculations of $\kappa_{tot}(\lambda)$ cover wavelength region 350nm $\leq \lambda \leq$ 500nm. The results of calculations are shown in Figs. 3 and 4 together with the corresponding experimental values $\kappa_{exp}(\lambda)$ of the spectral absorbtion coefficient from Vitel et al. (2004). This figures show the results of the calculations of $\kappa_{tot}(\lambda)$ in the case $\Delta_n = const.$, with the values of Δ_n and δ_n which are treated as optimal ones: $\Delta_n = 0.455$eV and $\delta_n = 0.625$eV for the short pulse, and $\Delta_n = 0.13$eV and $\delta_n = 0.11$eV for the long pulse.

Here it is important to check whether relation Eq. (4) is valid also for N_e close to $0.65 \cdot 10^{19}\mathrm{cm}^{-3}$. Since in the case of constant shifts $\Delta_n = 0.455$eV and 0.130eV for short and long pulses respectively, validity of Eq. (4) means that $0.455/0.130 = (1.5/0.65)^{3/2}$, which is satisfied with an accuracy better than 1%. In the case of variable shift we have it that $\Delta_{n=2} = 0.49$eV and $0.12eV$ for the short and long pulses respectively, and validity of Eq. (4) means now that $0.49/0.14 = (1.5/0.65)^{3/2}$, which is satisfied with the same accuracy. The fact that Eq. (4) is satisfied for $N_e = 1.5 \cdot 10^{19}\mathrm{cm}^{-3}$ and $0.65 \cdot 10^{19}\mathrm{cm}^{-3}$ offers a possibility to determine Δ_n or $\Delta_{n=2}$ not only for these densities but also for any N_e from interval $0.65 \cdot 10^{19}\mathrm{cm}^{-3} < N_e < 1.5 \cdot 10^{19}\mathrm{cm}^{-3}$ and probably in a significantly wider region. Also, using the fact that the influence of δ_n over the absorbtion coefficients is significantly weaker than the influence of Δ_n, we can determine the values of δ_n for any N_e using the values of ratio δ_n/Δ_n from the considered examples.

On the grounds of all that was said one can conclude that the presented method can already be used for calculations of the spectral absorbtion coefficients of dense hydrogen plasmas with $N_e \sim 10^{19}\mathrm{cm}^{-3}$ and $T_e \approx 2 \cdot 10^4\mathrm{K}$. Let us note that, with some minor modifications, the presented method can be applied to any kind of dense single-ionized plasma (laboratorial alkali-metal plasmas, helium plasmas in some DB white dwarfs etc.

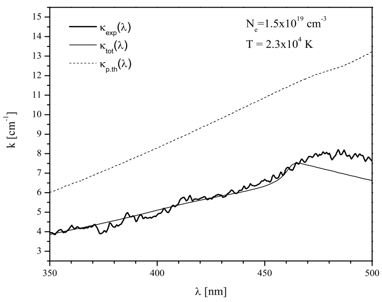

Figure 3: The absorbtion coefficient $\kappa_{tot}(\lambda)$ calculated in the case of the short pulse with $\Delta_n = 0.455$eV and $\delta_n = 0.625$eV. Dashed line - the theoretical curve from Vitel et al. (2004).

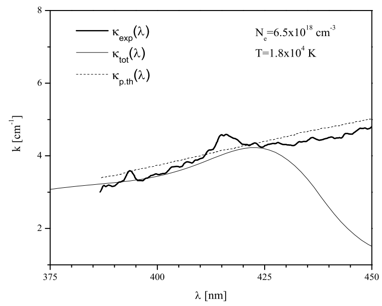

Figure 4: The absorbtion coefficient $\kappa_{tot}(\lambda)$ calculated in the case of the Long pulse with $\Delta_n = 0.13$eV and $\delta_n = 0.11$eV. Dashed line - the theoretical curve from Vitel et al. (2004).

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